Gallium Oxide and Its Applications in Electronics: An Overview

F. ZIKA[1], M. ALBAGUL[1], W. ZHANG[1], S. A. CHODAVARAPU[1], R. QUAGLIA[1], A. ALBAGUL[2]
[1]Department of Electrical and Electronic Engineering,
Cardiff University,
Queen's Buildings, 14-17 The Parade, Cardiff CF24 3AA,
UNITED KINGDOM

[2]Libyan Authority for Scientific Research
Tripoli
LIBYA

Abstract: Gallium oxide (Ga_2O_3), a semiconductor, has recently attracted the attention of many researchers and specialists due to its large band gap and thermal stability, which has made it widely used in several fields, including modern electronics and optoelectronics. In this paper, the many forms and properties of gallium oxide materials will be highlighted, as well as a complete analysis of their distinctive properties. The synthesis and fabrication procedures will also be discussed, which may shed light on the problems and progress made in this field. Some of the most common applications of gallium oxide will also be explored, including flash memory devices and gas sensors, in addition to its future use in data storage and environmental monitoring technology. In addition, an overview of the commercial prospects will be provided, with expectations indicating significant growth in the market, with an estimated increase of 44% by 2033, which will contribute significantly to the semiconductor industry.

Key-Words: - Gallium Oxide (Ga_2O_3), Ultrawide Band Gap, CZ and EFG Techniques, Power Electronics and EVs, Gas Sensors, Market Growth, Environmental and Health Impacts.

Received: April 17, 2024. Revised: October 21, 2024. Accepted: November 4, 2024. Published: December 6, 2024.

1 Introduction

In recent years, materials used in the semiconductor industry have attracted many researchers in order to keep pace with the technological development that has led to many innovations in several fields, including electronics, energy systems, and communications. Among these materials that have attracted research is gallium oxide (Ga_2O_3), which has become the focus of attention due to its wide band gap properties that provide unique advantages over traditional semiconductors such as silicon carbide (SiC) and gallium nitride (GaN), [1]. With the increasing demand for efficient industries, the need for materials that can operate under harsh conditions while maintaining reliability and cost-effectiveness has increased. From this standpoint, it can be said that gallium oxide, with its interesting electronic properties, has been favored by many researchers as a potential choice for these challenges [2]. Since gallium oxide is one of the materials that show polymorphism, it is available in multiple structural forms, each with distinct properties [3]. As a result of this diversity of shapes, researchers and engineers have the opportunity to deal flexibly in designing devices designed for specific applications. For example, the β phase of Ga_2O_3, which is the most stable and widely studied polymorph, exhibits a band gap of about 4.8 eV, making it one of the most important, if not the most attractive, elements for the manufacture of high-power and high-temperature electronics [1]. All of these properties are of great importance in demanding applications such as power electronics, where efficiency and thermal stability are of paramount importance [2]. In this paper, gallium oxide semiconductors will be presented and studied in terms of their material structure, properties, main manufacturing processes, methods, and applications. An overview of the composition of gallium oxide, its various types, and their distinctive properties will be provided [4]. Since these structural differences greatly affect the electrical and optical properties of the material, making it suitable for various advanced applications in electronics and optoelectronics [5]. The manufacturing processes of gallium oxide are equally important for its commercial viability. Both conventional and advanced manufacturing methods therefore improve material quality, reduce costs, and increase scalability. From vapor-phase layering to molecular beam epitaxy, this paper will highlight the key technologies used to produce gallium oxide semiconductors and their implications for large-scale industrial production [6]. In this paper, two specific applications of gallium oxide, namely flash memory devices and gas sensing technology, will be presented in detail. Since flash memory is an essential component in modern data storage systems, it is likely to witness significant development by taking advantage of gallium oxide's high-speed performance and robustness [7]. Furthermore, gallium oxide, which has the ability to sense various gases, along with its chemical durability, has become an important player in the manufacture of new generation gas sensing devices, especially in safety-critical environments [8].

The growing economic and commercial expansion of gallium oxide will be discussed in addition to its technological aspects. According to market data and projections, gallium oxide is expected to expand by 44% by 2033 and become a significant participant in the semiconductor industry going forward. Its improved performance in a variety of applications is the reason for this rise, which is anticipated to help progress sectors from aerospace to the automotive sector [9], [10].

However, with the increased use of gallium oxide comes important considerations regarding environmental and health concerns. The paper will discuss the potential impacts of gallium oxide's extraction, production, and disposal on the environment and public health, [10]. As the semiconductor industry advances, it is essential to ensure that the benefits of gallium oxide do not come at the expense of sustainability and ethical responsibility.

2 Material

Gallium Oxide is a III-V group ultra-wide band gap semiconductor resulting from a chemical reaction between Gallium and Oxygen. Gallium usually cannot be found in nature. It exists in the earth's crust, where its abundance is about 16.9 ppm. It is extracted from bauxite and sometimes sphalerite. Gallium can also be found in coal, diaspore, and germinate. Figure 1 shows an image of the Gallium material and Figure 2 shows the periodic table represents the Gallium and Oxide material. Figure 3 shows the atomic structures of Gallium Oxygen, [10].

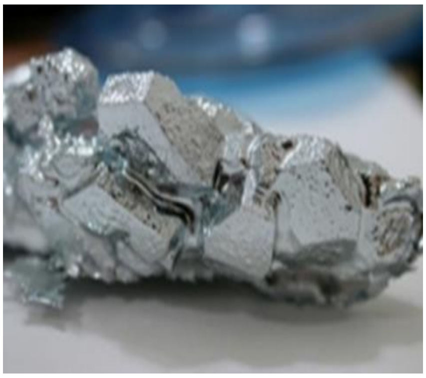


Fig. 1: Gallium material

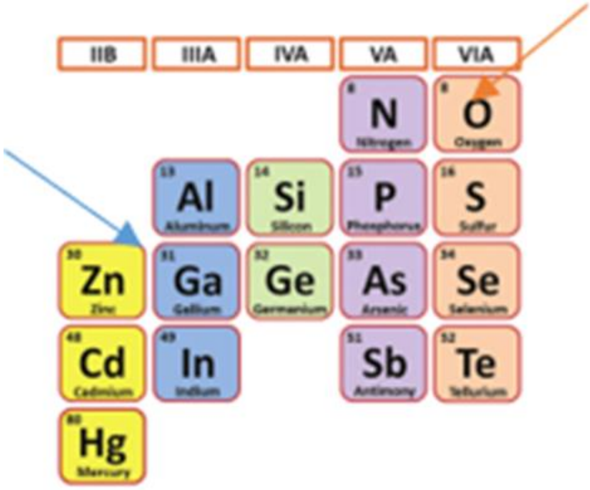
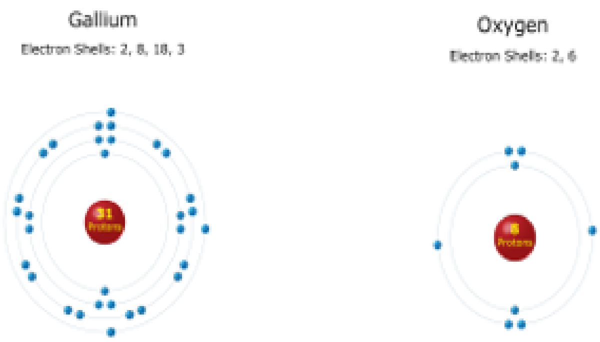


Fig. 2: Periodic table represents the Gallium and Oxide material



(a) Gullium (b) Oxygen

Fig. 3: Atomic structure

There are several forms of Gallium-Oxide in terms of crystal structure called polymorphs. Each polymorph has its preparation method and properties.

2.1 α-Ga2O3 Polymorph

α-Ga_2O_3 can be obtained by heating β-Ga_2O_3 at 65 kbar and 1100 °C. It has a corundum structure. The hydrated form can be prepared by decomposing precipitated and "aged" gallium hydroxide at 500 °C. Figure 4 shows the crystalline structure of α-Ga_2O_3 polymorph, [10].

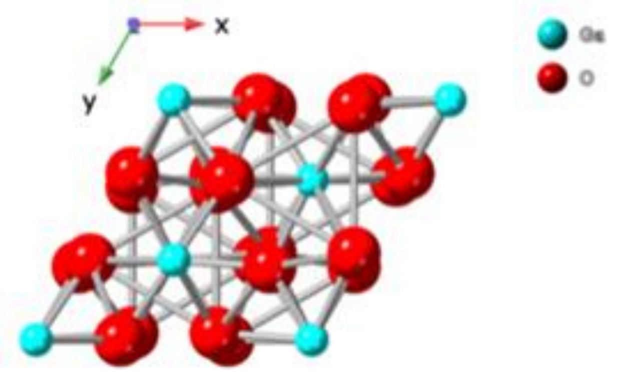


Fig. 4: Crystallin structure of α-Ga_2O_3 polymorph

2.2 γ-Ga_2O_3 Polymorph

γ-Ga_2O_3 is prepared by rapidly heating the hydroxide gel at 400–500 °C. A more crystalline form of this polymorph can be prepared directly from gallium metal by a solvothermal synthesis. It is the least stable polymorph Figure 5 shows the crystallin structure of γ-Ga_2O_3 polymorph, [10].

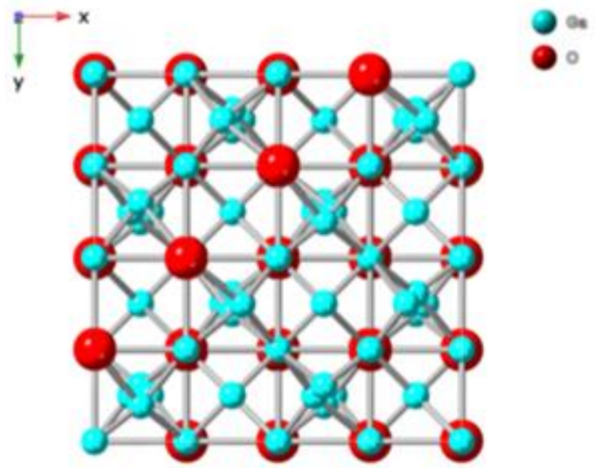


Fig. 5: Crystallin structure of γ-Ga_2O_3 polymorph

2.3 β-Ga_2O_3 Polymorph

β-Ga2O3 epitaxial thin films can be deposited heteroepitaxial on substrates such as sapphire, GaN, SiC, and Si, as well as homoepitaxial. For example, ALD on sapphire substrates at temperatures between 190 °C and 550 °C have been demonstrated. [11], high-quality β-Ga_2O_3 films have also been grown using techniques such as MBE, HVPE, and MOPVE, [12]. HVPE is preferred for vertical power semiconductor devices due to its fast growth rate, [13]. β-Ga_2O_3 epitaxial films grown by MOVPE exhibit higher electron mobilities and lower background carrier concentration than those grown by other thin-film growth techniques. Figure 6 shows the crystalline structure of β-Ga_2O_3 polymorph, [14], [15].

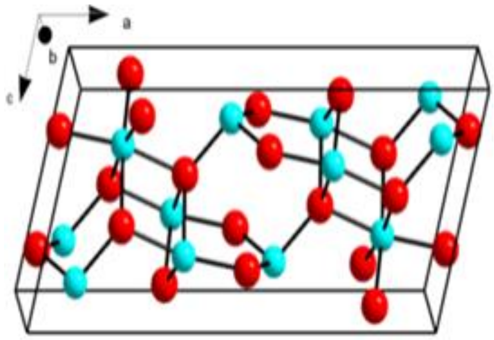


Fig. 6: Crystallin structure of β-Ga_2O_3 polymorph

3 Properties

Semiconductor materials can be broadly categorized into four generations based on the sequence in which they became important for scientific study and applications. The first generation of semiconductors was made of silicon and germanium, [16]. A Germanium single crystal was used to create the first semiconductor transistor. However, its relatively narrow bandgap, susceptibility to temperature changes, and lack of an appropriate insulating layer limit the number of devices that can be produced, [17]. Typically, second-generation semiconductor materials have a relatively narrow bandgap and emit red or infrared light, which is ineffective in the visible light spectrum, particularly the blue-green spectrum, which is needed for everyday illumination. This challenge was not resolved until the appearance of gallium nitride, a typical material of the III-V group of semiconductors. Wide bandgap semiconductors are typically referred to as third-generation semiconductors. Apart from gallium nitride, the third generation includes silicon carbide, aluminum gallium nitrogen, and others, [16]. Not only are they used for illumination, but they can also be used for high-current and high voltage switching, [17]. The third generation of semiconductor power devices is likewise highly remarkable. The term "fourth generation" semiconductors refers to a wide range of material systems with various application objectives in mind. Some of these material systems are compound semiconductors, like indium arsenide and gallium antimonide, with narrower band gaps that aim for more effective infrared and even mid-infrared detection and luminescence. Certain materials, such as gallium oxide or aluminum nitride, have ultra-wide bandgaps and are intended for use in power devices that must withstand high temperatures, high currents, or high voltages. Certain low-dimensional materials, such as two-dimensional atomic crystal materials or carbonbased nanomaterials, are being studied to find novel device applications and physical effects, [18]. Table 1 lists a comparison of the characteristics of several typical semiconductor materials to understand the characteristics of gallium oxide.

Table 1. Comparison of property data for different generations of semiconductor materials

Generation	1st	2nd		3rd		4th		
Materiels	Si	GaAs	Inp	4H-SiC	GaN	AlN	β-Ga2O3	adamas
Band Gap (eV)	1.12	1.43	1.3	3.3	3.4	6.2	4.2~4.9	5.5
relative dielectric constant	11.7	13.1	12.5	9.7	9.8	8.5	10	5.5
Insulation breakdown field strength (W/cm·K)	0.3	0.6	0.5	2.5	3.3	2	8	10
Thermal conductivity	1.5	0.55	0.7	2.7	2.1	3.2	0.23[010] 0.13[100]	10
Electron mobility (cm2/V·s)	1400	8500	5400	1000	1200	135	300	2000
Baliga Merit Value	1	15	-	340	870	-	3444	24664

This part will mainly discuss the four properties of gallium oxide and analyze the advantages and disadvantages of the material.

3.1 Ultra-Wide Band Gap

Firstly, there is the ultra-wide bandgap. The energy differential between a semiconductor material's valence and conduction bands is known as the bandgap. The band gap of gallium oxide is quite broad and usually exceeds 4.5 eV. Also, the large bandgap is a result of both its electrical and crystal structures. Gallium oxide is resistant to electric fields and high temperatures because of the space between energy bands. Additionally, it can continue to function electrically well in high-temperature and high-pressure environments thanks to its broad bandgap. In high-speed electronic applications, a balance between conductivity and band gap is essential, as this can also result in limiting the speed of electronic devices, [19].

3.2 High Critical Breakdown Field Strength

The second crucial characteristic is a high voltage breakdown. The voltage at which a substance changes from an insulator to a conductor is known as the breakdown voltage. The breakdown voltage of gallium oxide is high, usually greater than 8 MV/cm. Because of its wide bandgap, gallium oxide has a high breakdown voltage, requiring more energy to break the bond. Additionally, this enables gallium oxide devices to function at greater voltages, enhancing the dependability and effectiveness of power electronic equipment. However, attaining high breakdown voltage could provide material engineering difficulties, such as performance-affecting crystal structural flaws, [19].

3.3 Lower Thermal Conductivity

Low heat conductivity is the subject of the third attribute. A material's capacity to conduct heat is known as its thermal conductivity. The thermal conductivity of gallium oxide is comparatively poor compared to other semiconductors. This is explained by the material's atom-to-atom interactions and the lattice's characteristics, [19]. Gallium oxide's low heat conductivity may be advantageous in applications where insulation is essential, like in some electrical systems. The low thermal conductivity of gallium oxide can also be problematic for applications of ineffective heat dissipation. A double-side cooling arrangement, as depicted in Figure 7, was suggested by Montgomery et al. during their investigation into ways to increase heat dissipation capacity, [20].

3.4 Lower Electron Mobility

Low electron mobility is the final characteristic examined. The speed at which electrons move through a material in response to an electric field is known as electronic mobility. Because of the material's intrinsic interactions and crystal structure, gallium oxide has a relatively low electron mobility, [19]. In some power devices, where control and conductivity must be balanced, reduced electron mobility can improve control. Gallium oxide's features may be advantageous in applications where precise electronic motion control is required. It should be remembered, though, that reduced electron mobility may restrict the high-speed uses of gallium oxide by limiting the speed of electrical devices. Figure 7 shows the double-side cooling geometric configuration of n-channel Ga_2O_3-based fin MOSFET.

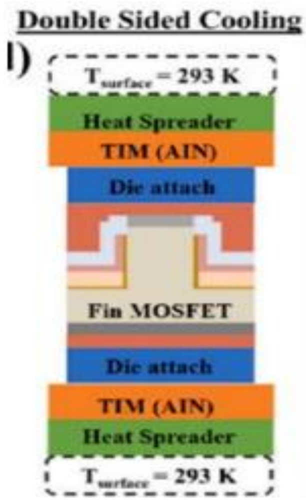


Fig. 7: Double side cooling geometric configuration of n-channel Ga_2O_3-based fin MOSFET

4 Fabrication

The most significant wafer growth technique in terms of business is melt growth. For many years, researchers have recognized β-Ga_2O_3 as a possible beneficial oxide semiconductor to develop a wide range of applications. The basis or need for fabricating large-diameter, high-structural-quality β-Ga_2O_3 single crystals from the melt sources, made the Czochralski method, Bernoulli process, Floating zone (FZ) process, Edge-defined film-fed growth (EFG) process, and others are applicable for wafer fabrication. In this study, the CZ method and EFG methods are primarily discussed.

4.1 CZ Method

The Czochralski method can have an array of designs, but it always consists of the following elements: an RF generator powering the inductive coil around the iridium crucible for heating, insulation within the growth chamber, a puller for pulling and rotating a growing crystal, a scale for weighing the growing crystal or the crucible for diameter control, and a control unit for controlling the generator's power in response to a scale signal that indicates a programmed growth rate these are the basic components involved respectively, [21]. The CZ method apparatus is illustrated in Figure 8.

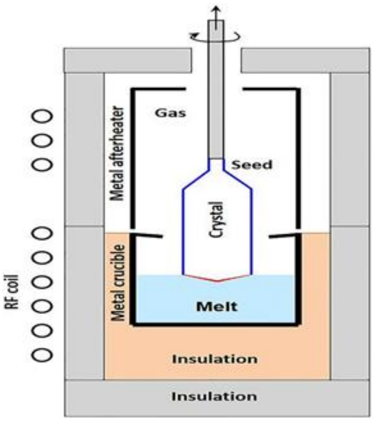
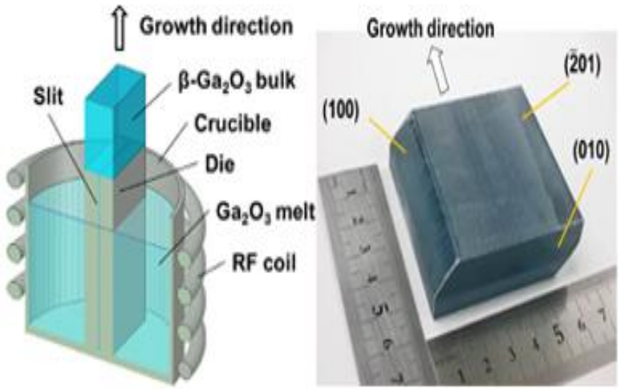


Fig. 8: CZ process apparatus

By combining the Ga_2O_3 decomposition and Iridium oxidation processes as a function of temperature, a special oxygen supply scheme to the growth furnace was designed and put into place to reduce the oxidation of the Ir crucible and other Ir parts in the furnace. This allowed the fabrication of single crystals of β-Ga_2O_3 with a diameter of 2 inches and a high structural quality which is very much necessary for different applications. The length of the crystals ranges from ≥ 6 cm to 2.5 cm for highly conducting and electrically insulating crystals, respectively. β-Ga_2O_3 single crystals can also be purposefully doped with various mono-to-tetra-valent ions to tune their optical and electrical characteristics, but this will also affect the stability of their growth. A wafer with varying orientations could be fabricated from the bulk crystals using this CZ method. The next bulk crystal fabrication method studied here is the Edge-defined film-fed growth (EFG) which is critically discussed in the following sections of this paper.

4.2 Edge-Defined Film-Fed Growth (EFG)

β-Ga_2O_3 growth rate is more when it is grown from a melt source. Compared to other wide-band-gap semiconductor materials like silicon carbide (SiC), graphene (GaN), aluminum nitride (AlN), and diamond (C), which can only be grown from diluted vapor sources and have relatively low growth rates, this indicates that it has a lower production cost, [22]. In the EFG method, 5N-grade Ga_2O_3 powder is used as the source material. To intentionally grow doped n-type crystals, tin dioxide (SnO_2) powder or silicon dioxide (SiO_2) powder was added to the Ga_2O_3 powder. The source powder was placed in a crucible made of iridium (Ir) together with an iridium die. The growth pressure was atmospheric pressure, and the growth atmosphere was a mixture of 98% nitrogen and 2% oxygen gas. The heating was carried out using a radio frequency (RF) induction coil. When the temperature reaches the melting point of β-Ga_2O_3, β-Ga_2O_3 melts at about 1800 °C when exposed to atmospheric pressure. The melt moved up through a slit in the iridium die by capillary action and reached the top surface of the die. The crystal growth was initiated by placing a β-Ga_2O_3 seed crystal in contact with the melt on the top surface of the die. In the EFG method, the shape of the grown crystal is usually determined by the shape of the top surface of the die. Figure 9 illustrates the schematic of the EFG apparatus and the crystal grown using this process.



(b) Apparatus (b) Sample crystal growth
Fig. 9: Schematic diagram of the EFG Method

4.3 Thin Film Growth Techniques

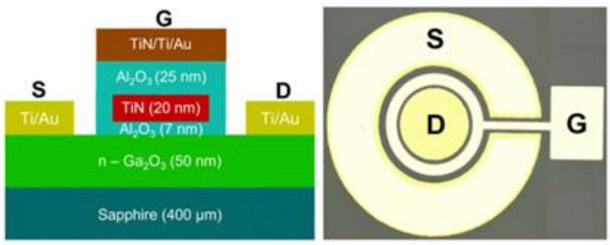
In addition to bulk crystal growth techniques for wafer fabrication, Gallium oxide can also be used as thin films grown either using homoepitaxy or hetero-epitaxially over a wide range of substrates. A few important techniques are briefly discussed in the following chapter of this study. Magnetron sputtering, chemical vapor deposition, pulsed laser deposition, and molecular beam epitaxy are among a few important methods used for this purpose, [23]. The Magnetron sputtering process requires a chamber and an environment that would facilitate the formation of gallium oxide thin films. Noble gas ions are used to bombard the target material and, due to this, there is a release of the particles from the material. These particles are then deposited over a substrate. The term ‘target’ is used to remove the material and deposit it on the substrate. Radiofrequency is used to vary the potential of the electric current in the process, which results in better cleaning of the target and helps in more deposition. Pulsed laser deposition uses a laser for deposition. The laser ablates the target, and the deposition takes place on a substrate. The process is generally performed in a chamber filled with various gases under constant pressure. The target and substrate are separated or placed apart from each other. This technique is very effective for thin films of gallium oxide on sapphire substrates. Molecular Beam Epitaxy (MBE) is a widely used technique, as it produces the best thin films of gallium oxide. The gallium oxide thin film nanomaterials that were prepared using the MBE process had the best structural quality, which depended on various parameters, such as the pressure of the oxygen, flow rate of oxygen, temperature of the substrate, and the formation of gases in the chamber.

5 Applications

Wide bandgap oxides can be used in different applications such as high-power and RF electronics, photodetectors, gas sensors, and electronics in extreme environments, [24]. This paper will focus on applications of the β polymorph of gallium oxide in flash memory devices, gas sensors, power electronics, and EVs.

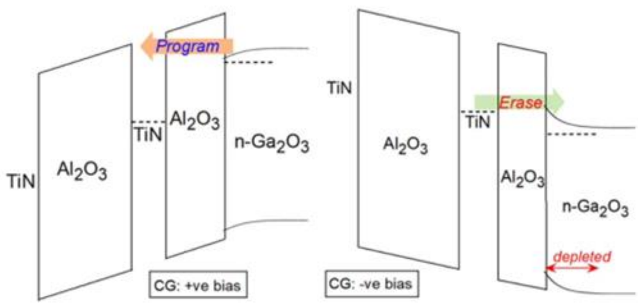
5.1 Gallium Oxide in Flash Memory Device

Gallium oxide devices are getting more interest due to their ability to withstand a range of temperatures and high radiation. Because of that, NASA and different research canters are experimenting with gallium oxide to make devices, especially for space exploration, [25]. The first application of β-gallium oxide is a flash memory device which is made to be used in space exploration missions. The research took place at KAUST (King Abdullah University of Science and Technology) and it was published in 2023. Unfortunately, the information about this application is limited because of how recent it is. The design that was used by the research team was the same as the ordinary flash memory device with the difference that instead of silicon, a layer of gallium oxide was used. The flash memory device was fabricated on a 50nm thick β-Ga_2O_3 film, grown on a c-plane sapphire substrate. Above the gallium oxide is a tiny fragment of titanium nitride, encased in a very thin layer of insulating material, which serves as the floating gate as shown in Figure 10. To program data into the floating gate, a positive voltage pulse was applied that sent the electrons from the gallium oxide, through the insulator and into the floating gate, where the electrons were trapped. The data were erased by applying a negative voltage which sent the electrons back into the gallium oxide as shown in Figure 11. A memory window greater than 4V was achieved by applying program/erase pulses of less than 20V in magnitude.



(b) cross-sectional (b) top view

Fig. 10: Gallium oxide flash memory device



(a) erasing (b) data.

Fig. 11: The changes in the energy bands of the materials during programming

The selection of gallium oxide over silicon was made due to its advantages. Gallium oxide can support high currents and voltages with low energy losses and it is easy to grow into high-quality films using low-cost techniques. It can also operate in adverse environments, especially in space, because it can withstand high temperatures and radiation without serious degradation. Gallium oxide has an unusually wide bandgap which translates to a distinct difference between the device's programmed and erased states, even at a high operating temperature. This property helps to make the memory very stable, with the prototype device retaining its data for over 80 minutes. The disadvantage is that programming and erasing the device requires relatively long voltage pulses of about 100 milliseconds, which the research team is trying to shorten, [25].

5.2 Gallium Oxide in Gas Sensor

One of the biggest obstacles to environmental sustainability, a healthy lifestyle, and the prevention and diagnosis of disease is the accurate, quick, and selective identification of inorganic and organic gases in indoor and outdoor air as well as industrial operations. Since the 1960s, metal oxides have been extensively investigated as extremely sensitive receptor elements in electronic gas sensors. Because of its exceptional chemical and thermal stability as well as its superior electrical properties, gallium oxide, which is frequently regarded as one of the wide-bandgap semiconductors, has demonstrated remarkable potential as an inorganic gas receptor, [26]. Ga_2O_3 is one of the materials that works well for gas sensing at high temperatures because of its melting point, which is approximately 1800^o C. When the operating temperatures are high, an oxygen deficiency inside the material dictates the sensing characteristics of binary oxides, causing them to behave similarly to N-type semiconductors. Beta gallium oxide, this structure remains stable across the whole temperature spectrum, right up to the melting point. The crystalline quality of Ga_2O_3 influences the performance of gas sensors at various operating temperatures. The transparent and colorless β-Ga_2O_3 single crystal was sliced into a nearly quadratic prism shape with dimensions of 8 mm in length, 5 mm in breadth, and around 1 mm in height. It was grown in dry air using the floating zone approach. Pt electrodes were applied as a pad type to a β-Ga_2O_3 single crystal using the ion-coating process. In another set of samples by using the RF magnetron sputtering process, thin layers of gallium oxide were sputtered and had a thickness of around 1 mm on a Si substrate also developed for sensing, [26]. Figure 12 depicts the sensing devices fabricated. Semiconducting β-Ga_2O_3 gas sensors, similar to other metal oxides, typically respond by altering resistance in response to changes in charge concentration, which arise from the interaction of gas molecules with the oxide surface. The semiconducting oxide surface of air (oxygen atmosphere) is thought to chemisorb O_2 molecules, trapping electrons from the conduction band and providing surface oxygen ions. The oxygen in the surrounding atmosphere and in the crystal, lattice is in dynamic equilibrium. If there is a reduction in the proportion of oxygen in the surrounding atmosphere, Ga_2O_3 crystal will experience an increase in the concentration of positively ionized oxygen defects in the lattice.

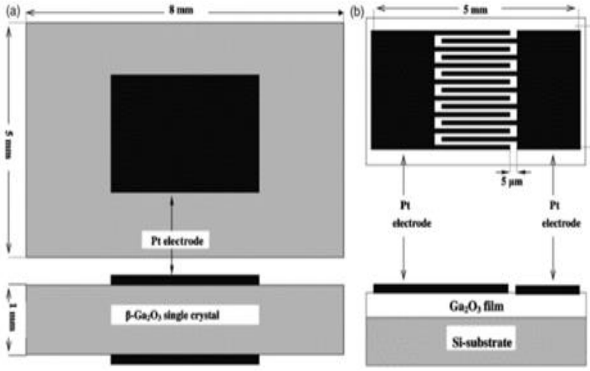


Fig. 12: Gas sensor schematics

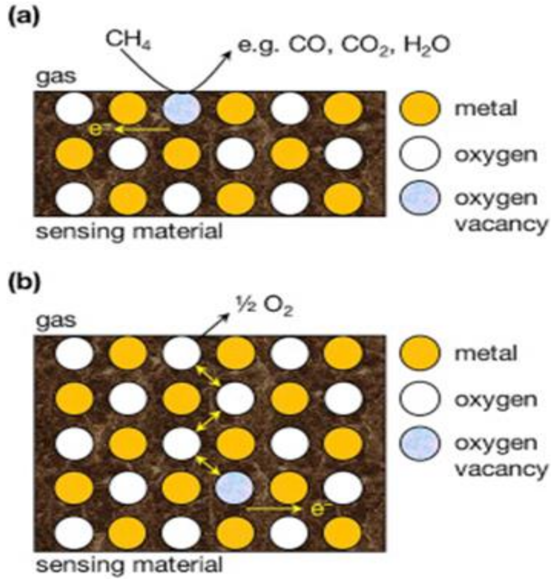


Fig. 13: Sensing mechanism illustration

Figure 13 illustrates the sensing mechanism. Sensing can be optimized by varying deposition techniques, source and/or substrate, and oxygen partial pressure. Ga_2O_3 thin films could be tuned to sense oxidizing or reducing gases by changing the operating temperature. Another way of improving the sensing mechanism is by reducing the working temperature of β-Ga_2O_3 gas sensors without trading off their sensitivity, stability, and reproducibility is also a great challenge.

5.3 Gallium Oxide for Power Electronics and Ev's

Silicon also has a comparatively low breakdown voltage, due to its inherent material properties, which makes it unreliable for power-switching applications. A reliable and efficient conversion usually involves switching circuits consisting of power electronics such as power diodes, power MOSFET, power rectifiers, thyristors, etc., along with suitable analog circuits supporting it. Wide bandgap (WBG) semiconductors such as gallium nitride (GaN), silicon carbide (SiC), gallium oxide (Ga_2O_3), diamond, etc. have come up as viable candidates to overcome the shortcomings, these UWBG materials usually have a high breakdown field as compared to conventional silicon. Ga_2O_3-based power electronic devices can not only withstand high temperatures but can also be employed in harsh radiation environments such as outer space, nuclear reactors, geothermal applications, multi-kilovolt-class substation equipment, power inverters for electric vehicles, industrial motor drives, etc [27]. It is because of this unique quality that gallium oxide is used in the inverters achieving MHz switching frequencies for ultrafast charging of the EVs, thus improving its range capabilities.

5.4 Commercial, Ethical, and Health

The estimated market cap is 1.2 million USD in 2023 with a CAGR of 44.1 % in 10 years, 46.4 million USD by 2033, [28] in which a major chunk of its growth is attributed to the APAC region. APAC is estimated to contribute 56% to the growth of the global market as shown in Figure 14. Major industrial sectors contributing to the rapid expansion of gallium oxide technology into their portfolio are petrochemicals, and automobiles respectively, [29].

Fig. 14: Global market distribution

Gallium radioactive compound, gallium (67Ga) citrate, can be injected into the body without harmful effects for radiological imaging. Long-term exposure to Gallium and gallium compounds like any other compound semiconductor may cause dermatitis and depression of the bone marrow function. Currently, mining solely for Ga extraction is not economical due to its low concentration. Gallium is mainly synthesized as a by-product from the processing of minerals and metals which has a range of environmental problems. Proper methods and techniques are under development to mitigate the environmental impact of this repurposing.

6 Conclusion

In conclusion, this paper has provided a comprehensive examination of gallium oxide (Ga_2O_3) and its essential significance within the electronics sector, highlighting its potential to facilitate substantial technological progress. The investigation into the various polymorphs, particularly β-Ga_2O_3, emphasizes the importance of this material in advanced research endeavors. By considering the basic and technical properties used in the composition of gallium oxide as well as Its applications, this paper illustrates the distinctive features of gallium oxide in terms of high thermal stability, wide band gap, and good electrical conductivity, all of which provide great opportunities for gallium oxide to be a key component in the electronic devices industry in the future. It can also be said that the use of gallium oxide In flash memory devices, gas sensors, powerful electronics, and electric vehicle converters has helped improve performance and efficiency and is able to extend the service life in many fields in terms of developing energy-saving devices. In addition, evaluating the long-term environmental and health effects of gallium oxide In common electronic applications can help promote responsible and sustainable development. Therefore, it can be said that gallium oxide has become an important material in the development of electronic industries due to its technological and vital advantages.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used GPT-4 in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References:

[1] Pearton, S.J., Ren, F., & Mastro, M. (2019). *Gallium Oxide Technology, Devices and Applications,* ISBN: 978-0-12-814521-0, https://doi.org/10.1016/C2017-0-01768-8.

[2] S. J. Pearton, Jiancheng Yang, Patrick H. Cary, F. Ren, Jihyun Kim, Marko J. Tadjer. Michael A. Mastro, A review of Ga2O3 materials, processing, and devices, *Appl. Phys. Rev.* 5, 011301 (2018), https://doi.org/10.1063/1.5006941.

[3] Liandi Li, Wei Wei, Malte Behrens (July 2012), Synthesis and characterization of α-, β, and γ-Ga2O3 prepared from aqueous solutions by controlled precipitation, *Solid State Sciences*, Vol. 14 (7), 971-981, doi: 10.1016/j.solidstatesciences.2012.04.037.

[4] Marezio, M.; Remeika, J. P. (1 March 1967). "Bond Lengths in the α-Ga2O3 Structure and the High-Pressure Phase of Ga2−xFexO3". *The Journal of Chemical Physics*. 46 (5): 1862–1865. doi: 10.1063/1.1840945.

[5] Helen Y. Playford, Dr. Alex C. Hannon, Dr. Emma R. Barney, Prof. Richard I. Walton (2013), Structures of Uncharacterised Polymorphs of Gallium Trioxide from Total Neutron Diffraction, *Chemistry: A European Journal*, 19 (8), 2803 –13, doi: 10.1002/chem.201203359.

[6] Takashi Matsumoto, Masaharu Aoki, Akira Kinoshita, Tomoyoshi Aono, (1974), Absorption and Reflection of Vapor Grown Single Crystal Platelets of β-Ga2O3, *Japanese Journal of Applied Physics*, Vol. 13, Number 10, doi: 10.1143/JJAP.13.1578.

[7] Jun Zhu, Zhihao Xu, Sihua Ha, Dongke Li, Kexiong Zhang, Hai Zhang, Jijun Feng, Gallium Oxide for Gas Sensor Applications: A Comprehensive Review, *Nanomaterials*, 2022, 12(12), 2061; https://doi.org/10.3390/nano12122061.

[8] Hong Zhou, Jincheng Zhang, Chunfu Zhang, Qian Feng, Shenglei Zhao, Peijun Ma, Yue Hao, A review of the most recent progresses of state-of-art gallium oxide power devices, *Journal of Semiconductors*, Vol. 40, Number 1, 2019, doi: 10.1088/1674-4926/40/1/011803.

[9] Jędrzejczyk, M., Zbudniewek, K., Rynkowski, J. et al. Wide band gap Ga2O3 as efficient UV-C photocatalyst for gas-phase degradation applications. *Environmental Science and Pollution Research Publishing model* 24, 26792–26805 (2017). https://doi.org/10.1007/s11356-017-0253-2.

[10] Playford, Helen Y.; Hannon, Alex C.; Barney, Emma R.; Walton, Richard I. (2013). "Structures of Uncharacterised Polymorphs of Gallium Trioxide from Total Neutron Diffraction". *Chemistry: A European Journal*. 19 (8): 2803–13.

[11] Rafie Borujeny, E.; Sendetskyi, O.; Fleischauer, M. D.; Cadien, K. C. (2020). "Low Thermal Budget Heteroepitaxial Gallium Oxide Thin Films Enabled by Atomic Layer Deposition". *ACS Applied Materials & Interfaces*. 12 (39): 44225-44237.

[12] Andrew J. Green, James Speck, Grace Xing, Peter Moens, Fredrik Allerstam; Krister Gumaelius, Thomas Neyer, Andrea Arias-Purdue, Vivek Mehrotra, Akito Kuramata, Kohei Sasaki, Shinya Watanabe, Kimiyoshi Koshi, John Blevins, Oliver Bierwagen, Sriram Krishnamoorthy, Kevin Leedy, Aaron R. Arehart, Adam T. Neal, Shin Mou, Steven A. Ringel, Avinash Kumar, Ankit Sharma, Krishnendu Ghosh, Uttam Singisetti, Wenshen Li, Kelson Chabak, Kyle Liddy, Ahmad Islam, Siddharth Rajan, Samuel Graham, Sukwon Choi, Zhe Cheng, Masataka Higashiwaki, February 2022), β-Gallium oxide power electronics, APL Materials, 10 (2), 029201-40, https://doi.org/10.1063/5.0060327.

[13] Yang, Duyoung; Kim, Byungsoo; Eom, Tae Hoon; Park, Yongjo; Jang, Ho Won (1 March 2022). "Epitaxial Growth of Alpha Gallium Oxide Thin Films on Sapphire Substrates for Electronic and Optoelectronic Devices: Progress and Perspective". *Electronic Materials Letters*. 18 (2): 113–128.

[14] Tsao, J. Y.; Chowdhury, S.; Hollis, M. A.; Jena, D.; Johnson, N. M.; Jones, K. A.; Kaplar, R. J.; Rajan, S.; Van de Walle, C. G.; Bellotti, E.; Chua, C. L.; Collazo, R.; Coltrin, M. E.; Cooper, J. A.; Evans, K. R. (2018). "Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges". *Advanced Electronic Materials*. 4 (1): 1600501.

[15] Zhang, Yuewei; Alema, Fikadu; Mauze, Akhil; Koksaldi, Onur S.; Miller, Ross; Osinsky, Andrei; Speck, James S. (1 February 2019). "MOCVD grown epitaxial β-Ga2O3 thin film with an electron mobility of 176 cm2/V s at room temperature". *APL Materials*. 7 (2): 022506.

[16] J. Green, Detailed Introduction to Three Generations of Semiconductor Materials, [Online].

https://www.sputtertargets.net/blog/introduction-to-the-generations-of-semiconductors.html (Accessed Date: October 13, 2024).

[17] Y. Zhang, 2020, The Application of Third Generation Semiconductor in Power Industry, *2020 10th Chinese Geosynthetics Conference & International Symposium on Civil Engineering and Geosynthetics (ISCEG 2020)*. China, Oct. 2020.

[18] Trunnano, 2022, Gallium Oxide as the Fourth Generation of Semiconductor Material, [Online]. https://www.nanotrun.com/blog/gallium-oxide-as-the-fourth-generation-of-semiconductor-material_b0464.html (Accessed Date: October 13, 2024).

[19] Kaur D, Ghosh A, Kumar M. A strategic review on gallium oxide-based power electronics: Recent progress and future prospects[J]. *Materials Today Communications*, 2022, 33: 104244.

[20] R.H. Montgomery, Y. Zhang, C. Yuan, S. Kim, J. Shi, T. Itoh, A. Mauze, S. Kumar, J. Speck, S. Graham, Thermal management strategies for gallium oxide vertical trench-fin MOSFETs, *J. Appl. Phys.* 129 (2021), 085301.

[21] Akito Kuramata1, Kimiyoshi Koshi1, Shinya Watanabe, Yu Yamaoka, Takekazu Masui, Shigenobu Yamakoshi, High-quality β-Ga2O3 single crystals grown by edge-defined film-fed growth, *Japanese Journal of Applied Physics* 55, 1202A2 (2016).

[22] Zbigniew Galazka2,1, Reinhard Uecker1, Detlef Klimm1, Klaus Irmscher1, Martin Naumann1, Mike Pietsch1, Albert Kwasniewski1, Rainer Bertram1, Steffen Ganschow1 and Matthias Bickermann1, Scaling-Up of Bulk β-Ga2O3 Single Crystals by the Czochralski Method, *ECS Journal of Solid-State Science and Technology*, Vol. 6, Number 2,2016.

[23] Jamwal NS, Kiani A. Gallium oxide nanostructures: A review of synthesis, properties and applications. *Nanomaterials (basel)*. 2022 Jun. 15, 12(12):2061. doi: 10.3390/nano12122061.

[24] Khandelwal, V., Rajbhar, M. K., Garcia, G. I. M., Tang, X., Sarkar, B., & Li, X. (2023b). Demonstration of β-Ga2O3 nonvolatile flash memory for oxide electronics. *Japanese Journal of Applied Physics*, 62(6), 060902.

[25] NASA TechPort. (n.d.). Project Data, [Online]. https://techport.nasa.gov/view/113274 (Accessed Date: October 13, 2024).

[26] A. Afzal, "B-ga2o3 nanowires and thin films for metal oxide semiconductor gas sensors: Sensing mechanisms and performance enhancement strategies," *Journal of Materiomics*, vol. 5, no. 4, pp. 542–557, 2019

[27] Bartic, M., Baban, C.-I., Suzuki, H., Ogita, M. and Isai, M. (2007), β-Gallium Oxide as Oxygen Gas Sensors at a High Temperature. *Journal of the American Ceramic Society*, 90: 2879-2884.

[28] "Market research reports - industry analysis size & trends - technavio," Gallium Oxide Market Size, Share & Trends [2023 Report], [Online]. https://www.technavio.com/report/gallium-oxide-market-analysis (Accessed Date: October 13, 2024).

[29] Fact.MR – gallium oxide market analysis by grade, global market insights 2023 to 2033," Fact.MR, Market Research Company, [Online]. https://www.factmr.com/report/2027/gallium-oxide-market (Accessed Date: October 13, 2024).

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- F. F. Zika1 contributed to the application section.
- M. Albagul contributed to the material section.
- W. Zhang contributed to properties section.
- S. A. Chodavarapu1 contributed to fabrication section.
- R. Quaglia contributed to the introduction and conclusions (supervisor).
- A. Albagul contributed to the editing and revising the whole paper.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This work is funded by EPSRC Center.

Conflict of Interest

The authors have no conflicts of interest to declare.